# Recreating the "Origins of the Elements" Planetarium Show and Curriculum Module

Research Thesis

Presented in Partial Fulfillment of the Requirements for graduation *with research distinction* in Astronomy in the undergraduate colleges of The Ohio State University


by

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July 2021


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## Acknowledgements

This thesis was supported by NSF grants AST-1108693 (original "Origins of the Elements" planetarium program) and AST-1715284 (updated program). Work in the OSU Arne Slettebak Planetarium was made possible by the Arne Slettebak Endowment which received primary support from generous gifts by Gerald and Ann Newsom and by David and Sheryl Price. Additional support for the Arne Slettebak Planetarium is provided by the Ohio State University Department of Astronomy.

I would like to thank my advisors, Professor Richard Pogge and Dr. Wayne Schlingman, for their invaluable advice, encouragement, and continued support during this project. I truly could not have asked for two better mentors to guide me through this project and my senior year. I would like to thank Anna Voelker for leading the 2020 Summer Undergraduate Research Program which introduced me to this project, even through the COVID-19 pandemic. I would also like to thank Krisann Stephany for creating the original "Origins of the Elements" planetarium program, without which this project would not be possible. Lastly, I would like to thank my family and friends for always believing in me and supporting my passions. A special thanks to my roommates and Gubby for keeping me company during a global pandemic.

# Contents

# 1 Introduction

In 2019, OSU Astronomy student Krisann Stephany created the "Origins of the Elements" planetarium show and curriculum module for the Arne Slettebak Planetarium at the Ohio State University (OSU). It was created as part of the Broader Impacts component of a National Science Foundation (NSF) grant to OSU Professor Richard Pogge. This program was designed to educate middle and high school students about the many ways in which elements are formed in our universe. The original objective of this thesis project was to adapt Krisann Stephany's planetarium show for the recently upgraded software in the Arne Slettebak Planetarium under the guidance of planetarium director Dr. Wayne Schlingman and Professor Richard Pogge.

Due to the COVID-19 pandemic, the planetarium was unfortunately not accessible at the time this project began. Thus, the objective of the project changed from simply adapting the show to entirely recreating it, using the information gained from piloting it the first time. This gave us the opportunity to focus on creating an engaging, educational, and well-structured narrative for the show before even stepping foot in the planetarium. This reinvented narrative of "Origins of the Elements" progresses through the periodic table from hydrogen to the heavy synthetic elements, discussing their origins by simultaneously progressing through stellar evolution and the history of the universe. Restructuring the show into a more logical progression is intended to make "Origins of the Elements" more captivating, memorable, and easier to follow. The introduction and conclusion of the show were redesigned to bring the story of the show into a wider context and help students understand the significance of the elements in their own lives.

Based upon this updated narrative structure, I developed a new script, new 3D graphics, and a detailed storyboard version of the show which can be found in Item A3 in Appendix A. This storyboard, along with my narration of the script, eventually became a product of its own in the form of a video adaptation of the show. The "Origins of the Elements" curriculum module was also updated to improve the classroom experience based on feedback from the pilot. The video adaptation of "Origins of the Elements" along with its updated curriculum module are intended to be distributed to middle school science classes as a distance-learning module. The major results of this project were the restructuring of the show, the creation of new graphics and a storyboard, and the completion of this distance-learning module. Moving forward, the video version of "Origins of the Elements" will be adapted for the Arne Slettebak Planetarium at OSU, aiming for completion in the summer of 2021.

# 2 Background

In the summer of 2020, I began working on this project as a part of the OSU Department of Astronomy's Summer Undergraduate Research Program (SURP), advised by Professor Richard Pogge and Dr. Wayne Schlingman. The initial objective of this project was to adapt Krisann Stephany's original "Origins of the Elements" planetarium show for the upgraded planetarium software in the Arne Slettebak Planetarium (DigitalSky – Dark Matter software). However, we had to change course and revise this objective due to the COVID-19 pandemic closing the planetarium. We decided instead to entirely rework the script, the accompanying visuals, and the curriculum module, focusing on creating a cohesive narrative which educates the audience in a way that is engaging yet easy to understand. This recreation of the "Origins of the Elements" planetarium show is a continuation of an NSF-sponsored outreach project, which is part of the Broader Impacts component of a collaborative research grant to study chemical abundances in nearby galaxies with the Large Binocular Telescope. The broader goal of this project is to educate the public on a related topic, the origins of the chemical elements, and contribute to the improvement of astronomy literacy. “Origins of the Elements” was specifically created with a middle school audience and science learning standards in mind.

According to the International Astronomical Union (IAU)’s proposed definition of astronomy literacy, the idea that “we are all made of stardust” is one of 11 essential astronomy concepts that all people should ideally understand [1]. This planetarium show aims to educate middle school audiences on this important concept by telling the story of the origins of the elements of which we are all made. One thing we learned from the pilot testing was to focus more on the audience experience. Not only is its goal to educate a middle school audience, but also to effectively engage them in the content and pique their interest in astronomy. Updating the curriculum module of “Origins of the Elements” further addresses this goal. The suite of materials includes various classroom materials, a lesson guide, and a distance-learning video to ensure that students will be well prepared to view the show and will retain more information after viewing the show. Additionally, the show and its curriculum module were created with the intention to address relevant Ohio Learning Standards (OLS) for Science and Next Generation Science Standards (NGSS) (see Item A1 in Appendix A).

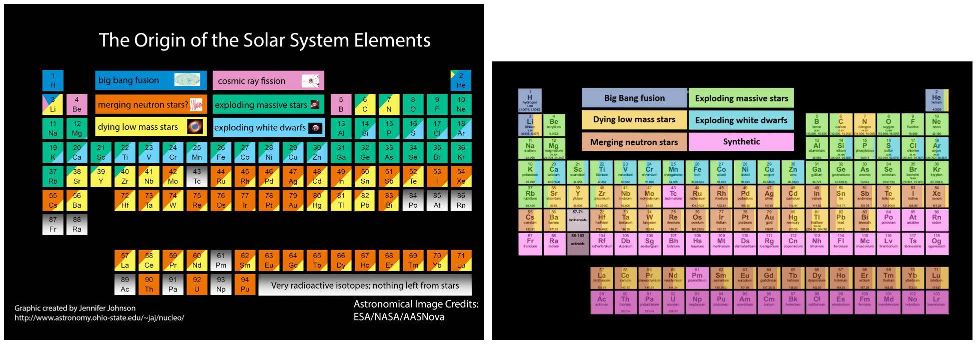
# 3 Video Adaptation

## 3.1 Rewriting the script and restructuring the narrative

We began the process of recreating “Origins of the Elements”, using Krisann Stephany’s original script as initial guidance. Krisann Stephany’s pilot testing of “Origins of the Elements” informed us of which aspects of the show worked well and which needed improvement. Students reported that the show was interesting and enjoyable. Another comment was that they had trouble digesting the large amount of information being presented. Others stated that the information seemed complicated by the use of unfamiliar technical language and their lack of background knowledge. Addressing this feedback became the main focus in the process of rewriting the script.

The show was simplified by choosing consistent language and only including details relevant to the essential concepts of the show. The intent is to make the content more approachable and accessible to students with little prior astronomy knowledge. For instance, we removed all instances of the term “isotope” in the script because it is not necessary to understanding the main concepts of the show. Although the show mentions many specific isotopes, we only refer to them as “heavier” or “lighter” types of the same element. This communicates the necessary information about these isotopes without using jargon that the students may not be familiar with yet. While using the term “isotope” and fully explaining its definition may give the students a more precise understanding, it may also overcomplicate the concept of elements and may unnecessarily confuse the students.

Some of Professor Pogge’s introductory astronomy lectures were also used to guide the rewriting process. Studying his lectures on the origins of the elements inspired an emphasis on developing a clear and engaging storyline in which each topic builds off the previous. The beginning of the show introduces the audience to the concepts of matter, atoms, and elements by using examples which are applicable to everyday life. This connects the content of the show to the lives of the audience members and motivates an interest in what follows. The conclusion serves a similar purpose by relating the essential concepts of the show back to the audience. Professor Jennifer Johnson’s “The Origin of the Solar System Elements” graphic, a periodic table color-coded by stellar origin (as shown in Fig. 1a), inspired the organization of the middle section of the show. Following the intro-




(a) (b)

Figure 1: Fig. 1a shows a periodic table with elements color-coded according to their origin. For instance, hydrogen is shown in blue, indicating by the legend at the top that it was made through Big Bang fusion. This graphic was created by Prof. Jennifer Johnson of the OSU Department of Astronomy [2]. Fig. 1b shows the complete recreation of Fig. 1a used in the show. Throughout the show, the table is color-coded by origin incrementally (Big Bang fusion first, then exploding massive stars, and so on). This shows the completed table from the end of the show.

duction, the show progresses through the periodic table, from atomic number 1 to 118, discussing their origins. Along the way, we fill in the periodic table according to their origins, effectively recreating the graphic shown in Fig. 1a. This recreation is shown in Fig. 1b. The narrative also follows a roughly chronological progression through the history of our universe. It begins at the Big Bang (creation of lightest elements), then moves to star formation, stellar fusion, supernovae, stellar remnants (creation of heavier elements), and ends at synthetic creation in modern day (creation of heaviest elements). This structure of the narrative is intended to make the content easier for the audience to follow and recall.

The script was also rewritten to address the current Ohio Learning Standards for Science and Next Generation Science Standards (NGSS) for 5th grade through high school. We intended to satisfy all the learning standards already covered by the new version of the show, which are listed in Item A1 of Appendix A. These became the essential concepts that were emphasized in the new version of the show. Some of the major ideas we wanted to communicate in the show were the concepts of matter, atoms, and elements, the structure of the periodic table, and basic knowledge about stars (what they are, how they form, how they produce elements, etc.). These satisfy the NGSS 5-PS1-1 learning standard and the Ohio Learning Standards PS.M.1, PS.M.2, and PS.U.3. The overarching concept of the show is the origins of the elements, which fulfills the NGSS HS-ESS1-3 learning standard. Following these learning standards ensures that students will benefit from watching the show and learn meaningful concepts which are relevant and appropriate to their grade level.

## 3.2 Creating and arranging new accompanying visuals

While writing the script, we began redeveloping the visual aspect of the show. Because we were initially restricted to working remotely, we decided to compile a rough sketch of the visuals we wanted to see during each section of the script in the form of a storyboard. This laid out a representation of the visuals intended to be projected on the planetarium dome and matched concepts to actions and diagrams with the associated language. This storyboard format can be seen in Fig. 2,

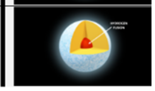
| TRANSITION | SCRIPT | |
|---|---|---|
| | These shortest-lived stars are called the massive stars, |  |
| **CLICK TRANSITION** **(zoom in to massive star)** | and they are 8 or more times the mass of our Sun. Just like all stars, a massive star begins its lifetime fusing |  |
| **CLICK TRANSITION** **(cut-away )** | hydrogen to helium in its core through a process called stellar fusion. A star of this size will spend about 3 million years in this hydrogen fusion stage! |  |

Figure 2: Example of a section of the storyboard, separated into three columns (transition, script, visual thumbnail). A presenter would read this table left-to-right. In other words, the presenter would read the script in the first row, then execute the transition in the second row, then read the script in the second row, and so on. The thumbnail is the post-transition visual.

and the full storyboard version of the show is given in Item A3 of Appendix A. The storyboarding process and explicit descriptions and actions made the process of implementing the show in the planetarium easier after reopening, and created an organized guide on how to narrate the show while progressing through each visual component for future planetarium presenters and teachers.

We developed this storyboard by determining what visuals should accompany each section of the script. Student feedback from the previous version of the show informed us that more dynamic, immersive, 3D visuals were needed. We selected and created visuals and transitions that would create an immersive experience in the planetarium using our newly available technology. After constructing a general idea of what visuals we wanted in the show, we first searched for already existing images and animations that demonstrate astronomy concepts well. For instance, we used several animations from the European Southern Observatory (ESO)'s video library, including two fulldome videos, and several images from NASA JPL. Fig. 3a contains one of these images (showing the W3 and W5 star forming regions), and Fig. 3b shows a still image taken from one of the fulldome videos (showing the Helix nebula).

I created several new graphics, animations, and 3D models to illustrate concepts in the show. These new visuals were created to be simple, clear, and only address relevant content. The new visuals communicate the concepts used in the show and are better suited for our middle school audience. They are also specifically tailored to the planetarium; They are intended to not only be educational, but also visually engaging and immersive when paired with the script, and they emphasize the use of technology now available to the planetarium.

One of these new visuals, which illustrates the fusion shells inside the core of a red supergiant, is shown in Fig. 4a. This visual was based on existing depictions of this concept commonly found in introductory astronomy textbooks, like the one shown in Fig. 4b, which shows the shells of fusion by cutting away a half hemisphere of the star. While this cut-away illustration is a great way to reveal what goes on inside the core of the star, it could be improved by showing the processes leading up to the image in Fig. 4b. Instead of using a still image, I attempted to animate this process of fusing progressively heavier elements in the core of a high mass star by first using simple shapes and built-in PowerPoint animations. A still image of this first draft is shown in Fig. 4c. The animation shows each flat "sphere" growing larger as another one grows at its center, pushing it out into a shell, which is intended to represent the accumulation of each element at the core until it is hot

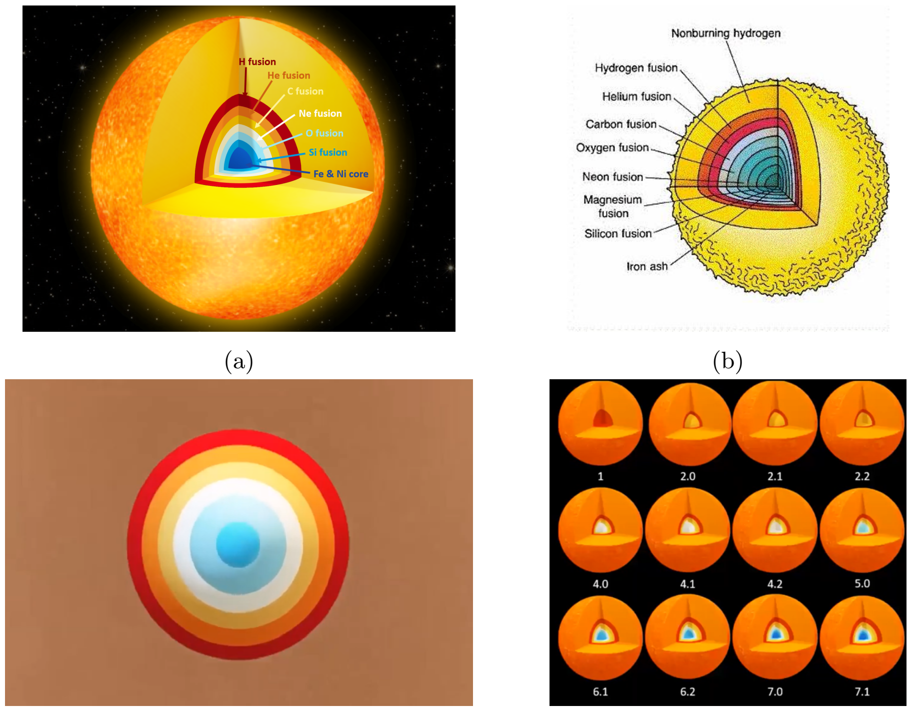
(a) (b)

Figure 3: Fig. 3a shows an image of the W3 and W5 star forming regions, from NASA's Spitzer Space Telescope and Wide-field Infrared Survey Explorer (WISE) Telescope [3]. Fig. 3b shows a still image taken from a fulldome video of the Helix nebula. This video was created by ESO using images from the Wide Field Imager (WFI) camera on the Max Planck Society/ESO telescope [4].

enough to ignite fusion of a heavier element. While this first draft communicates the concept (when accompanied with a proper verbal explanation), it is not as accurate or engaging as it could be. To improve upon this, I made 3D models to represent each stage in the progression, as shown in Fig. 4d. The first model shows the hydrogen fusion in the core, the next models shows the hydrogen fusion shell around the helium fusion in the core, the next show the hydrogen and helium fusion shells around the carbon fusion in the core, and so on. These 3D models were then made into a simple animation by fading each one over top of the last. Compared to the still image in Fig. 4b or the initial animation attempt shown in Fig. 4c, this final draft animation shown in Fig. 4a is more engaging and makes it easier for students to visualize the process.

Although we still had to take some artistic license in creating this visual, it is more accurate than the textbook diagram. I created the outer texture of the 3D models based on simulations of convection and radiation at the surface of red supergiants and recreated images of Betelgeuse [5, 6]. These images were overlaid and lightly edited for clarity and aesthetic purposes. For instance, I brightened the image and slightly adjusted the coloring to improve the contrast with the background and outer envelope. While this makes it less accurate, it makes it easier for the audience to view and understand. Additionally, the size of the core and fusion shells relative to the outer envelope was decreased significantly from the textbook diagram. This is more accurate and gives the audience a visual understanding that the core takes up a small proportion of the star's volume. The relative size of the core and fusion shells are still very inaccurate in the new visual, but it was necessary to make them significantly larger than reality in order to communicate the concept clearly. While these changes make the visual less realistic, it improves readability and preserves ease of understanding.

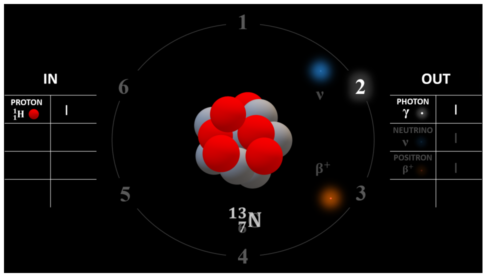
Another new visual created for "Origins of the Elements" is a depiction of the Carbon-Nitrogen-Oxygen (CNO) cycle, shown in Fig. 5a and Fig. 5b. Textbook diagrams were used as a jumping-off point in creating this visual. An example of this type of diagram is shown in Fig. 5c. While this type of diagram does communicate the concept, a student with no previous knowledge of the CNO cycle or fusion reactions may be overwhelmed and confused. When students look at these diagrams, they may not know where to look first, and it may not be very intuitive to understand because it is a cyclical process. While the new visual does include a still image depicting the entire CNO cycle like



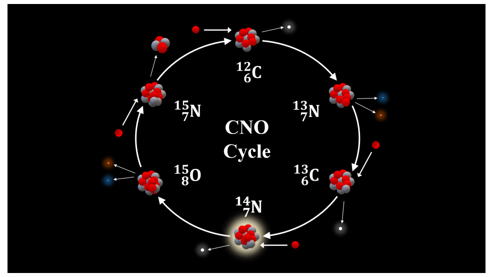

(a) (b) (c) (d)

Figure 4: Fig. 4a shows a still image from the final draft of the massive star visual, depicting the fusion shells and core inside a massive star. This is the version used in the video. Fig. 4b shows an example of similar diagrams commonly found in textbooks. This image comes from Pearson Prentice Hall [7]. Fig. 4c shows a still image from the first draft of the massive star visual. Its rings represent the layers of fusion shells inside the star. Fig. 4d shows some of the 3D models used in the creation of Fig. 4a. Each model shows a stage in the progression of stellar fusion.

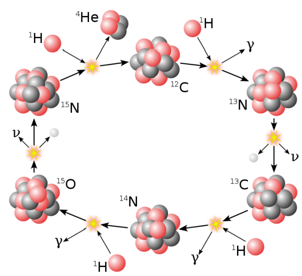
the common textbook diagram, it is preceded by an animation that goes through each individual step of the cycle. This guides the audience through the entire cycle in small, easily comprehensible sections, detailing the products and reactants involved in each fusion reaction before displaying the cycle as a whole. For instance, Fig. 5a is a screen capture from the animation of the second step in the CNO cycle, in which a proton of nitrogen-13 undergoes beta decay, emitting a neutrino and a positron, converting the nitrogen-13 to carbon-13. There are also tables shown on the side of the screen, keeping track of the particles which go “in” the nucleus (reactants) and “out” of the nucleus (products) at each step. By the end, the audience sees from these tables that four protons were added to the nucleus, and one helium atom is the main product of one iteration of the CNO cycle. This animated section of the CNO cycle visual gives the audience a detailed look at each step of CNO cycle while also giving an impression of the overall result. This also makes it clear as to why this cycle takes place inside the hydrogen fusion shell in a star, as its reactants are hydrogen nuclei, and its product is helium. After this animation, the CNO cycle is shown in its entirety, as in Fig. 5b. This makes it easy for the audience to visualize how the individual steps fit together in the cycle. It also allows the presenter to highlight the fourth step to show the importance of the CNO cycle in nitrogen-14 production. Here, they can explain that this step takes significantly longer than any other, and that the majority of cycles would be waiting in this stage of nitrogen-14 at any given




(a)




(b)




(c)

Figure 5: Fig. 5a shows a still image taken from the CNO cycle animation used in the video version of the show. It depicts the second step of the CNO cycle in which a proton undergoes $\beta^+$ decay. Inventory tables on the side of the image tally the reactants and products after each fusion reaction in the cycle. Fig. 5b shows the static CNO cycle visual used in the video version of the show. It illustrates the entirety of the CNO cycle with the fourth stage (nitrogen-14) highlighted. Fig. 5c shows an example of a common depiction of the CNO-I Cycle [8].

time. This makes the CNO cycle's relevance to the show clear.

### 3.3 Assembling the video adaptation

After realizing that COVID-19 closures would last longer than initially expected, this remotely created storyboard format of the show was turned into a product of its own. Despite being created on a flat screen using PowerPoint slides to organize them, the storyboard visuals flowed well and looked surprisingly polished on their own. We decided that it should be recorded and turned into a video adaptation of a planetarium show and could be used as part of a distance-learning module for middle school science classes during the COVID-19 pandemic and beyond. This process involved recording the visuals, recording my narration of the script, captioning the video, and uploading it to YouTube [9]. We then planned to distribute this video to middle school science classes in Ohio, but first needed an updated lesson plan to accompany this new version of "Origins of the Elements".

## 4 Updated Curriculum Module

Following the completion of the video adaptation of "Origins of the Elements", a curriculum module was created to accompany both the video adaptation and the actual planetarium show once it is completed. This lesson plan was designed to prepare students to watch the show by ensuring that they had the necessary background knowledge to understand it fully. Although the show itself does not assume much prior knowledge, preparing the students beforehand by introducing or reviewing relevant concepts allows them to enjoy viewing "Origins of the Elements", reinforcing the new information they learned in class during the show.

Krisann Stephany created a curriculum module to accompany her original version of the show, which we used as a starting point for the updated version. We consulted the student feedback from the original version to inform what changes should be made, and looked at the updated show for new concepts and vocabulary explored. Feedback showed that there was a lot of new information combined with unfamiliar terminology presented in the show. We needed to make sure that the relevant concepts were easier to recall in the new version of the show. While it is expected that much of the content in "Origins of the Elements" will be unfamiliar to middle school students, we can make it easier for them to learn this new information by establishing consistent terminology and introducing some concepts in advance in the classroom. Feedback showed us where we could provide new lesson materials to further prepare students for the planetarium show.

We began updating the parts of Krisann Stephany's original lesson plan which we thought worked well. For instance, I modified the vocabulary list to include only the terminology used in the updated show. I discarded the terms "astronomical unit", "magnitude", "neutron capture", and "black hole", because they were either irrelevant to or were not specifically mentioned by name in the new version of the show. As an example, we deliberately excluded "black hole" because, while it is a topic that interests many students, it is unnecessary to understanding the origins of the elements. On the other hand, we excluded "neutron capture" not because it was irrelevant to the show, but because it is not mentioned by name in the show (to avoid overwhelming the viewer with too much new information). I also added new terms that were used in the updated version of the show (but not in the original version) and created an answer key to the vocabulary list for teachers' reference.

We included the "KWL Activity" (Know, Want to know, Learned) from Krisann Stephany's original lesson plan, which asks students to first write down what they already know about the content in "Origins of the Elements" and what they wish to learn from the show, and then after viewing the show, report what they learned. This gives students confidence in their current knowledge and encourages them to be curious about the topics covered in the show. It will demonstrate their progress throughout the curriculum module by reminding them of their initial knowledge and goals for learning and then showing how those goals were achieved.

Two new activities were also created as suggested by Krisann's work: one focusing on the CNO cycle and another focusing on elements. The CNO Cycle Activity involves putting the students in groups of six to act out the six steps of the CNO cycle. This gives teachers the opportunity to incorporate an aspect of kinesthetic learning in the curriculum module and compliments the CNO cycle animation that they will see in the show. The entirety of the CNO Cycle Activity can be found in Item A2 of Appendix A. The Elements Activity asks students to choose one element to study and put together a brief report, poster, or presentation to share what they have learned about the element. This introduces an opportunity for independent learning and developing presentation skills. These activities are merely suggestions which teachers can modify or build upon as they see fit. This is intended to allow teachers to customize the lesson plan to fit their teaching style and their students' learning styles. However, a next step for this project would be to develop complete activity guides, including detailed instructions, a list of required materials, and a video demonstration of the activity. These activities would also ideally be tested by groups of students and modified based on feedback.

| | | |
|---|---|---|
| 16 |  | **How do stars die?** Low mass stars.<br>Image of the Helix nebula located in the Aquarius constellation. The gases from the outer envelope and fusion shells are expanding away from the carbon-oxygen core that was left behind.<br>Note: “Planetary nebula” is a misnomer; It has nothing to do with planets. It was named this way because they sometimes resemble gas giant planets from a distance. |

Figure 6: An example of the slide descriptions included with the slide decks in the curriculum module. This is a description of a slide in the ”Stars” slide deck picturing the Helix nebula as an example of a planetary nebula. It goes into greater detail about the Helix nebula and planetary nebulae in general for the teachers’ reference without cluttering the slide.

Lastly, I created three sets of PowerPoint slide decks containing background information on three main content areas of the show: “Atoms and Elements”, “Fusion, Fission, and Radioactivity”, and “Stars”. These are intended to provide necessary background knowledge to understand and enjoy “Origins of the Elements”. Reviewing this information before watching the show allows students to focus on learning about the origins of the elements instead of requiring them to learn about atoms, elements, the Big Bang, fusion, radioactivity, and stellar evolution all in one sitting. These sets of slides provide yet another opportunity for the teachers to customize the lesson plan to their classroom. For instance, if a class has not yet covered any of these topics in depth (or needs to review them), the teacher can choose to go through all three sets of slides over the course of a few days before viewing the show. On the other hand, if a class has already learned a good deal about atoms, elements, and radioactivity, the teacher may decide that they only need to go through the ”Stars” slides and half of the ”Fusion, Fission, and Radioactivity” slides, which may only take one day of preparation before viewing the show. Teachers may alternatively choose to present some or all of the slides after the show to reinforce the concepts learned during the show. Detailed descriptions of the slides were also created to accompany each set, including explanations of diagrams and additional information for teachers’ reference. An example of these descriptions is shown in Fig. 6.

A lesson guide was adapted from the original curriculum module to organize the new classroom materials with the old materials into a practical schedule. This guide informs teachers of all the materials provided and gives suggestions on how they may be used in combination with each other and the show itself. For instance, the guide suggests using the vocabulary list in the following way: First, have students fill out the terms they think they already know to get a sense of their initial background knowledge and misconceptions (i.e., assessing what they already know and what still needs to be taught or reviewed via the sets of slides). Then, have them complete the vocabulary list as guided notes for the sets of slides or as a post-assessment after going through the slides. However, teachers could deviate from the lesson guide and instead use the vocabulary list as guided notes for the show itself, or as a homework assignment if they see fit. While the guide outlines a two-day lesson plan, more material is provided than can reasonably be covered in two days, assuming an hour-long class. Again, this allows teachers to adapt the curriculum module to their individual classroom, using only what their students need, saving time and effort.

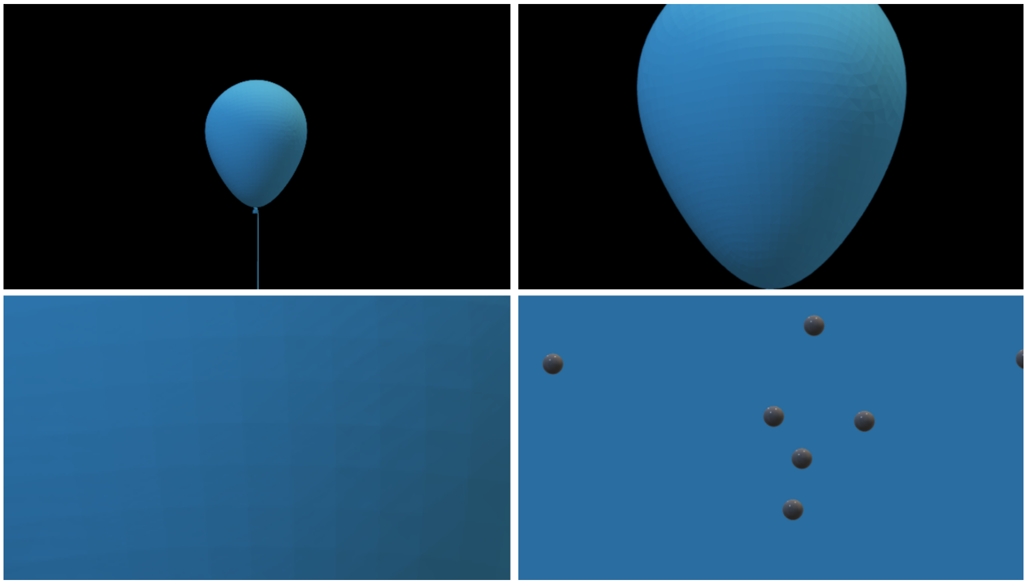


Figure 7: Still images taken from the video adaptation. This shows the progression of the scene (from left to right, top to bottom) in which the viewer is taken inside of a balloon to view its atoms. When implemented in the planetarium, the 3D model of this balloon is used, and the blue background grows to engulf the entire dome to appear as if the audience were entering the balloon.

# 5 Planetarium Implementation

In the summer of 2021, we began adapting the storyboard and video versions of "Origins of the Elements" for the planetarium. This final version of the updated show will follow the storyboard closely, with small changes to make better use of the immersive planetarium medium. Although several of the new animations were simply recorded and put onto slides to project on the planetarium dome, we attempted to make even these flat images and videos more immersive through various means. For instance, in the introduction of the show, the concept of atoms is introduced by looking at the helium atoms inside a balloon. In the planetarium version of the show, I used a 3D model of a balloon to make it appear as though the viewer is flying into the balloon and viewing its atoms from the inside. The video version of this scene is shown in Fig. 7. Additionally, some of the 3D star models (shown in Fig. 4d) were adapted and imported as 3D objects which can be rotated, moved, and attached to other objects in 3D. This utilizes the unique advantages of the planetarium to create a more immersive, dynamic experience. The use of 3D objects instead of flat images also affords the presenter more freedom to customize the show for their teaching style and particular audience. They can interact with the 3D objects in ways they see fit to enhance their instruction, instead of strictly following a script. The planetarium also allows us to use the fulldome videos (like the one shown in Fig. 3b) for their intended purpose of surrounding the audience. This translation from flat video to fulldome experience helps address the student feedback and broader goals of the project. Creating dynamic, fulldome, 3D visuals and allowing freedom for modification helps ensure a more engaging, memorable educational experience for the students. These visuals will immerse the students in their learning, helping them focus and develop a better spatial understanding of the concepts in the show.

# 6 Conclusion

While the original plan for the "Origins of the Elements" project was derailed due to the COVID-19 pandemic, working remotely allowed us to focus entirely on the organization of the show, the narrative, the new visuals, and the lesson plan without having to worry about the technical details of implementing it in the planetarium at the same time. This was an unexpected advantage for the project. We were able to address student feedback by simplifying the narrative to follow a chronological progression from the Big Bang to modern day and a simultaneous progression building the periodic table of elements. The new visuals are more immersive and dynamic than before, creating visually engaging models and animations to communicate astronomy concepts more effectively. We also addressed previous students' comments about the large amount of new information being presented by removing unnecessary jargon from the show and creating more classroom materials for teachers to use in preparation for viewing the show. The content of the classroom material was also simplified, and consistent language was established. Through this recreation process, we have also successfully addressed our broader goals: to educate the audience on the origins of the chemical elements, and to improve the audience's understanding of the essential idea that "we are made of stardust".

From the new script and visuals, the restructured narrative, the new video adaptation of the show, and the updated curriculum module, "Origins of the Elements" has been entirely recreated over the past 15 months. While we preserved many parts of the previous version, maintained the original purpose of the show, and continued to satisfy learning standards set by the Ohio Department of Education and NGSS, "Origins of the Elements" is now more engaging, immersive, and enjoyable for middle school students of all educational backgrounds. Finally, with the planetarium implementation of the show in progress, we will soon complete the original objective of this project by adapting "Origins of the Elements" for the new DigitalSky - Dark Matter software in the Arne Slettebak Planetarium. We expect that this final, recreated version of "Origins of the Elements" will be completed and ready for presentation in the summer of 2021.

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[9]OSU Astronomy, *Origins of the Elements - Planetarium Show*, Retrieved from YouTube. URL: www.youtube.com/watch?v=Vm2wN$_{d}0_{m}Aab_{c}hannel = OSUAstronomy$, 2020.

# A Appendix

## A.1 Learning Standards Addressed

### 5th Grade

#### NGSS

*5-PS1-1.* Develop a model to describe that matter is made of particles too small to be seen. [Clarification Statement: Examples of evidence supporting a model could include adding air to expand a basketball, compressing air in a syringe, dissolving sugar in water, and evaporating salt water.] [Assessment Boundary: Assessment does not include the atomic-scale mechanism of evaporation and condensation or defining the unseen particles.]

#### OLS

*5.ESS.2.* The sun is one of many stars that exist in the universe. The sun appears to be the largest star in the sky because it is the closest star to Earth. Some stars are larger than the sun and some stars are smaller than the sun.

### 6th Grade

#### OLS

*6.PS.1.* Matter is made up of small particles called atoms. Matter has mass, volume and density and is made up of particles called atoms. Elements are a class of substances composed of a single kind of atom. Molecules are the combination of two or more atoms that are joined together chemically.

### 7th Grade

#### OLS

*7.PS.1.* Elements can be organized by properties. Elements can be classified as metals, non-metals and metalloids, and can be organized by similar properties such as color, solubility, hardness, density, conductivity, melting point and boiling point, viscosity, and malleability.

### High School

#### NGSS

*HS-PS1-5.* Apply scientific principles and evidence to provide an explanation about the effects of changing the temperature or concentration of the reacting particles on the rate at which a reaction occurs. [Clarification Statement: Emphasis is on student reasoning that focuses on the number and energy of collisions between molecules.] [Assessment Boundary:

Assessment is limited to simple reactions in which there are only two reactants; evidence from temperature, concentration, and rate data; and qualitative relationships between rate and temperature.]

*HS-PS1-8.* Develop models to illustrate the changes in the composition of the nucleus of the atom and the energy released during the processes of fission, fusion, and radioactive decay. [Clarification Statement: Emphasis is on simple qualitative models, such as pictures or diagrams, and on the scale of energy released in nuclear processes relative to other kinds of transformations.] [Assessment Boundary: Assessment does not include quantitative calculation of energy released. Assessment is limited to alpha, beta, and gamma radioactive decays.]

*HS-ESS1-1.* Develop a model based on evidence to illustrate the life span of the sun and the role of nuclear fusion in the sun's core to release energy that eventually reaches Earth in the form of radiation. [Clarification Statement: Emphasis is on the energy transfer mechanisms that allow energy from nuclear fusion in the sun's core to reach Earth. Examples of evidence for the model include observations of the masses and lifetimes of other stars, as well as the ways that the sun's radiation varies due to sudden solar flares ("space weather"), the 11-year sunspot cycle, and non-cyclic variations over centuries.] [Assessment Boundary: Assessment does not include details of the atomic and sub-atomic processes involved with the sun's nuclear fusion.]

*HS-ESS1-2.* Construct an explanation of the Big Bang theory based on astronomical evidence of light spectra, motion of distant galaxies, and composition of matter in the universe. [Clarification Statement: Emphasis is on the astronomical evidence of the red shift of light from galaxies as an indication that the universe is currently expanding, the cosmic microwave background as the remnant radiation from the Big Bang, and the observed composition of ordinary matter of the universe, primarily found in stars and interstellar gases (from the spectra of electromagnetic radiation from stars), which matches that predicted by the Big Bang theory (3/4 hydrogen and 1/4 helium).]

*HS-ESS1-3.* Communicate scientific ideas about the way stars, over their life cycle, produce elements. [Clarification Statement: Emphasis is on the way nucleosynthesis, and therefore the different elements created, varies as a function of the mass of a star and the stage of its lifetime.] [Assessment Boundary: Details of the many different nucleosynthesis pathways for stars of differing masses are not assessed.]

**OLS**

*PS.M.1 Atoms.* Content introduced in middle school, where the atom was introduced as a small, indestructible sphere, is further developed in the physical science syllabus. Over time, technology was introduced that allowed the atom to be studied in more detail. The atom is composed of protons, neutrons and electrons that have measurable properties, including mass and, in the case of protons and electrons, a characteristic charge. When bombarding thin gold foil with atomic-sized, positively charged, highspeed particles, a few of the particles were deflected slightly from their straight-line path. Even fewer bounced back toward the source. This evidence indicates that most of an atom is empty space with a very small positively charged nucleus. This experiment and other evidence indicate the nucleus is composed of protons and neutrons, and electrons that move about in the empty space that surrounds the nucleus. Additional experimental evidence that led to the development of other historic atomic models will be addressed in the chemistry syllabus. All atoms of a particular element have the same atomic number; an element may have different isotopes with different mass numbers. Atoms may gain or lose valence electrons to become anions or cations. Atomic number, mass number, charge and identity of the element can be determined from the numbers of protons, neutrons and electrons. Each element has a unique atomic spectrum that can be observed and used to identify an element. Atomic mass and explanations about how atomic spectra are produced are addressed in the chemistry syllabus.

*PS.M.2 Periodic Trends of the Elements.* Content from the middle school level, specifically the properties of metals and nonmetals and their positions on the periodic table, is further expanded in this course. When elements are listed in order of increasing atomic number, the same sequence of properties appears over and over again; this is the periodic law. The periodic table is arranged so that elements with similar chemical and physical properties are in the same group or family. Metalloids are elements that have some properties of metals and some properties of nonmetals. Metals, nonmetals, metalloids, periods and groups or families including the alkali metals, alkaline earth metals, halogens and noble gases can be identified by their position on the periodic table. Elements in Groups 1, 2 and 17 have characteristic ionic charges that will be used in this course to predict the formulas of compounds. Other trends in the periodic table (e.g., atomic radius, electronegativity, ionization energies) are found in the chemistry syllabus.

*PS.M.4 Chemical Reactions.* While chemical changes involve changes in the electrons, nuclear reactions involve changes to the nucleus and involve much larger energies than chemical reactions. The strong nuclear force is the attractive force that binds protons and neutrons together in the nucleus. While the nuclear force is extremely weak at most distances, over the very short distances present in the nucleus the force is greater than the repulsive electrical forces among protons. When the attractive nuclear forces and repulsive electrical forces in the nucleus are not balanced, the nucleus is unstable. Through radioactive decay, the unstable nucleus emits radiation in the form of very fast-moving particles and energy to produce a new nucleus, thus changing the identity of the element. Nuclei that undergo this process are said to be radioactive. Radioactive isotopes have several medical applications. The radiation they release can be used to kill undesired cells (e.g., cancer cells). Radioisotopes can be introduced into the body to show the flow of materials in biological processes. For any radioisotope, the half-life is unique and constant. Graphs can be constructed that show the amount of a radioisotope that remains as a function of time and can be interpreted to determine the value of the half-life. Half-life values are used in radioactive dating. Other examples of nuclear processes include nuclear fission and nuclear fusion. Nuclear fission involves splitting a large nucleus into smaller nuclei, releasing large quantities of energy. Nuclear fusion is the joining of smaller nuclei into a larger nucleus accompanied by the release of large quantities of energy. Nuclear fusion is the process responsible for formation of all the elements in the universe beyond helium and the energy of the sun and the stars. Further details about nuclear processes including common types of nuclear radiation, predicting the products of nuclear decay, mass-energy equivalence and nuclear power applications are addressed in the chemistry and physics syllabi.

*PS.U.1 The Universe.* In early elementary school, observations of the sky and space are the foundation for developing a deeper knowledge of the solar system. In late elementary school, the parts of the solar system are introduced, including characteristics of the sun and planets, orbits and celestial bodies. At the middle school level, energy, waves, gravity and density are emphasized in the physical sciences, and characteristics and patterns within the solar system are found. In the physical science course, the universe and galaxies are introduced, building upon the previous knowledge about space and the solar system in the earlier grades. The Big Bang Model is a broadly accepted theory for the origin and evolution of our universe. It postulates that 12 to 14 billion years ago, the portion of the universe seen today was only a few millimeters across (NASA). According to the "big bang" theory, the contents of the known universe expanded explosively into existence from a hot, dense state 13.7 billion years ago (NAEP 2009). After the big bang, the universe expanded quickly (and continues to expand) and then cooled down enough for atoms to form. Gravity pulled the atoms together into gas clouds that eventually became stars, which comprise young galaxies. Foundations for the big bang model can be included to introduce the supporting evidence for the expansion of the known universe (e.g., Hubble's law and red shift or cosmic microwave background radiation). A discussion of Hubble's law and red shift is found in the Galaxy formation section, below. Technology provides the basis for many new discoveries related to space and the universe. Visual, radio and x-ray telescopes collect information from across the entire electromagnetic spectrum; computers are used to manage data and complicated computations; space probes send back data and materials from remote parts of the solar system; and accelerators provide subatomic particle energies that simulate conditions in the stars and in the early history of the universe before stars formed

*PS.U.3 Stars* Early in the formation of the universe stars coalesced out of clouds of hydrogen and helium and clumped together by gravitational attraction into galaxies. When heated to a sufficiently high temperature by gravitational attraction, stars begin nuclear reactions, which convert matter to energy and fuse the lighter elements into heavier ones. These and other fusion processes in stars have led to the formation of all the other elements. (NAEP 2009). All of the elements, except for hydrogen and helium, originated from the nuclear fusion reactions of stars (College Board Standards for College Success, 2009). Stars are classified by their color, size, luminosity and mass. A Hertzprung Russell diagram must be used to estimate the sizes of stars and predict how stars will evolve. Most stars fall on the main sequence of the H-R diagram, a diagonal band running from the bright hot stars on the upper left to the dim cool stars on the lower right. A star's mass determines the star's place on the main sequence and how long it will stay there. Patterns of stellar evolution are based on the mass of the star. Stars begin to collapse as the core energy dissipates. Nuclear reactions outside the core cause expansion of the star, eventually leading to the collapse of the star. Note: Names of stars and naming the evolutionary stage of a star from memory will not be assessed. The emphasis is on the interpretation of data (using diagrams and charts) and the criteria and processes needed to make those determinations.

## A.2 CNO Cycle Activity Suggestion

Split into groups of 6, stand or sit in a circle. Pretend each group is an instance of the CNO cycle occurring in the hydrogen fusion shell of an intermediate mass star. Begin with 4 protons available to be picked up. If in person, these could be slips of paper with a "p" on them. Have photons, positrons, and neutrinos available for them to "emit". Also have one helium-4 nucleus available. Have a designated "output" area to put any emitted particles.

**1.** 1st person reenacts the 1st step of the cycle. They represent carbon-12. They should pick up a proton, and then emit a photon in response. They would choose the photon and put it in the output area. They have now turned into nitrogen-13, as they gained a proton.

**2.** 2nd person reenacts the 2nd step of the cycle. They represent nitrogen-13. They should emit a positron and a neutrino, because they are unstable. They would choose the positron and neutrino and put it in the output area. They have now decayed into carbon-13, as one of their protons has transformed into a neutron.

... (Steps 3-5) ...

**6.** 6th person reenacts 6th step of the cycle, representing nitrogen-15. They should pick up a proton, then emit a helium-4 nucleus. They would put this helium-4 nucleus in the output area. Now they represent carbon-12, which is what the cycle started with.

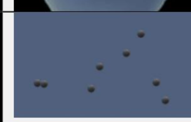
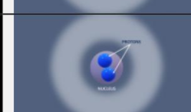
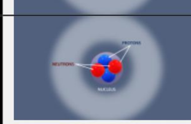
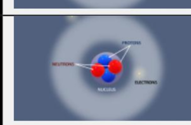
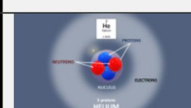
The 6th person could now reenact the 1st step in the 2nd run of the cycle (everyone will shift down 1 step). You could run through the cycle a few times to show that it begins again with carbon-12, and that carbon-12 is never "output" from the cycle. If running several times, make sure to start with enough protons, photons, positrons, neutrinos, and helium-4 nuclei.

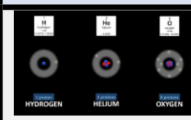
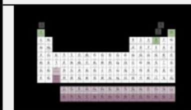
Demonstrating nitrogen-14 production: You could also have all groups going through the cycle at the same time, with appropriate timing for each step. Stagger the starting of each group by about 1 minute. The students representing steps 1, 2, 3, 5, and 6 take 5 seconds to complete their step (or as quickly as they can complete it). The person representing the 4th step takes 1 full minute to complete their step. Several minutes after all groups have begun their cycle, say "Stop!" at a random time. This represents the moment in the star's life when the outer envelope and fusion shells are ejected, freezing the CNO cycle. Record which step of the cycle each group was in when they stopped. Count how many groups were in step 4 (nitrogen-14). Most of the groups/cycles should be in the 4th step. This shows why the CNO cycle is so important for production of nitrogen-14, even though it is only one step in the cycle and is merely a catalyst. Most of the instances of the CNO cycle in a star at any given time are in the form of nitrogen-14 because this step takes much longer than the others.

## A.3 Storyboard Format

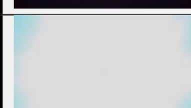
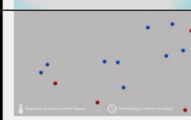
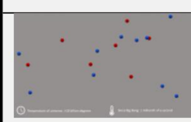
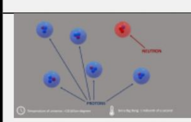
(Begins on next page.)

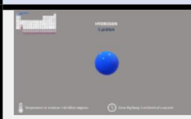
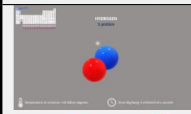
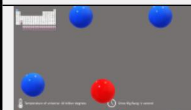
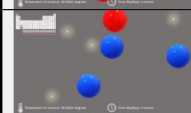
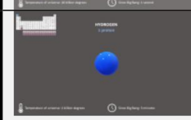
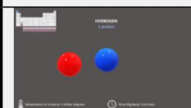
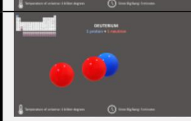
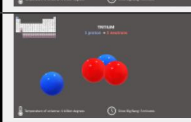
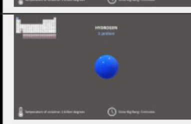
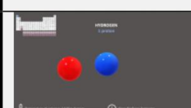
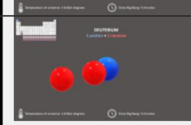
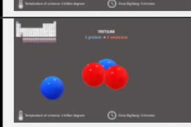
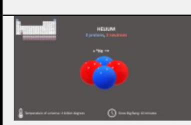
# INTRODUCTION

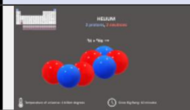
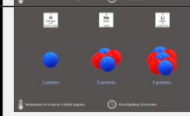
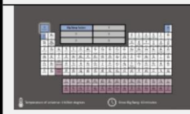
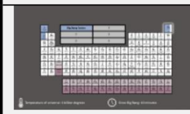
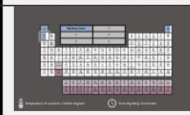
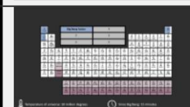
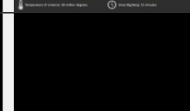
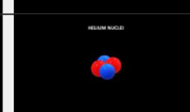
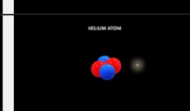
| TRANSITION | SCRIPT | |
|---|---|---|
| **(stars)** | Take a look around you, and notice all the things you see. You might see your teacher and your classmates sitting next to you, the walls of the planetarium, the seat you're sitting in, maybe you see your backpack. |  |
| **NEXT SLIDE (stars and moon)** | Or you might look up at the night sky and see the moon and the stars. But what are all of these different things made of? To answer this complex question, let's use something simple and familiar as an example first. |  |
| **NEXT SLIDE (fade to balloon)** | Take this common helium balloon for example. What is it made of? Looking from the outside, you might say it's made of some rubbery material, and a string. |  |
| **CLICK TRANSITION (zooms in to balloon)** | But if we go inside the balloon and take a look at what it's made of at the most basic level, what will we see? |  |
| **NEXT SLIDE (atom movement, zoom into one atom)** | First, we see tons of tiny particles called atoms bouncing around everywhere. |  |
| **NEXT SLIDE (zoom closer to one atom)** | Then, if we zoom in even closer, we see that these atoms are actually made up of even tinier particles. |  |
| **(fade to labeled nucleus)** | At the center of the atom we see a nucleus, containing |  |
| **CLICK TRANSITION (labeled protons appear)** | positively charged particles called protons, |  |
| **CLICK TRANSITION (labeled neutrons appear)** | and uncharged particles called neutrons. |  |
| **CLICK TRANSITION (labeled electrons appear and move)** | In the outer part of the atom we see tiny, negatively charged particles called electrons.<br>Atoms like these make up more than just the gas in balloons. Essentially everything we see around us is made up of atoms. |  |
| **CLICK TRANSITION (He symbol appears)** | But the atom we're seeing here is a specific type of atom called helium. This is just one of the many types of atoms in our universe, which we call the elements. |  |
| **NEXT SLIDE (fade to element examples)** | For instance, there's also hydrogen, an element found in the water we drink. And there's also oxygen, an element found in the air that we breathe. |  |

| TRANSITION | SCRIPT | |
|---|---|---|
| **CLICK TRANSITION (highlight proton number)** | Notice that each of these atoms has a unique number of protons - This is what differentiates the elements from one another. |  |
| **NEXT SLIDE (periodic table; H, He, O symbols move)** | This number is also used to organize the elements in the periodic table, which displays all 118 known elements in our universe. |  |
| **NEXT SLIDE (fade to stars)** | So now that we know that the matter we see around us is all made of elements, you might wonder, where did these elements come from? All of the elements we know of today didn't exist at the very beginning of the universe, so how were they made as the universe evolved? How did we come to be? |  |

BIG BANG FUSION

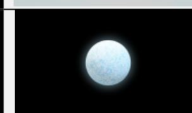
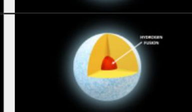
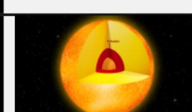
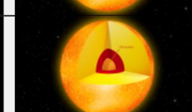
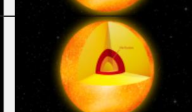
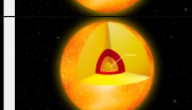
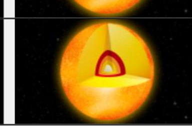
| TRANSITION | SCRIPT | |
|---|---|---|
| | Let's find out by going back to the very beginning. |  |
| **NEXT SLIDE (zooms in to black)** | Nearly 14 billion years ago, the universe is born. This moment is referred to as the "big bang". |  |
| **CLICK TRANSITION (play Big Bang video)** | The universe was initially incredibly hot and dense, and as time passed, the universe expanded and cooled rapidly. |  |
| **(Screen goes white)** | When only a trillionth of a second had passed, the universe had cooled to about 1 trillion degrees. |  |
| **NEXT SLIDE (fades from white to quark movement)** | At this point, the universe was full of tiny particles called quarks, and was densely packed with particles of light called photons. This is why we see a very bright universe here, instead of the darkness we see in our night sky today. |  |
| **(fades to darker grey)** | As the universe continued to expand, it eventually became cool enough that these quarks were able to form larger types of |  |
| **(hadrons form, labels appear)** | particles called hadrons. This includes the protons and neutrons that are found in atoms. |  |
| **NEXT SLIDE (zooms into proton)** | This marks the birth of our first element, hydrogen, whose nucleus is composed of a single proton. |  |

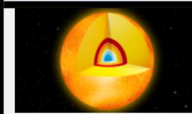
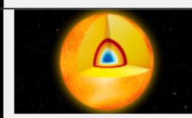
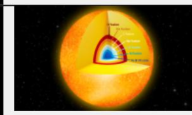
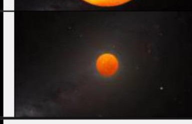
| TRANSITION | SCRIPT | |
|---|---|---|
| **NEXT SLIDE (fades to solid sphere and labels)** | At this point, only about a millionth of a second had passed since the big bang! The universe was a little more than 10 billion degrees, which was too hot for any other elements to form. |  |
| **CLICK TRANSITION (formation and destruction of deuterium)** | Any heavier nuclei would have been broken apart by a photon just as quickly as they were formed. |  |
| **NEXT SLIDE (moving protons & neutrons)** | Once the universe was 1 second old, it reached a temperature of 10 billion degrees. |  |
| **CLICK TRANSITION (electrons appear and move)** | At this point in time, electrons began for form. We now have all three components of an atom – protons, neutrons, and electrons. |  |
| **NEXT SLIDE (fades back to single proton)** | The universe continued to expand, finally reaching a cool temperature of about 1 billion degrees, 3 minutes after the big bang. This temperature was just in the right range for heavier elements to finally form through a process called big bang fusion. |  |
| **CLICK TRANSITION (deuterium forms)** | When a neutron collides with a hydrogen nucleus, they stick together, forming a heavier hydrogen nucleus called deuterium. |  |
| **(tritium forms)** | When another neutron collides with deuterium, an even heavier hydrogen nucleus called tritium is formed. |  |
| **(helium forms)** | Then, another light hydrogen nucleus (a single proton) collides with the tritium, creating a nucleus with two protons – Our second element, helium. |  |
| **NEXT SLIDE (fades back to single proton)** | The universe continued to expand, finally reaching a cool temperature of about 1 billion degrees, 3 minutes after the big bang. This temperature was just in the right range for heavier elements to finally form through a process called big bang fusion. |  |
| **CLICK TRANSITION (deuterium forms)** | When a neutron collides with a hydrogen nucleus, they stick together, forming a heavier hydrogen nucleus called deuterium. |  |
| **(tritium forms)** | When another neutron collides with deuterium, an even heavier hydrogen nucleus called tritium is formed. |  |
| **(helium forms)** | Then, another light hydrogen nucleus (a single proton) collides with the tritium, creating a nucleus with two protons – Our second element, helium. |  |
| **NEXT SLIDE (helium)** | During this time period, some slightly heavier elements were able to form as well, but only a very small amount of these elements was created. The most abundant of these heavier elements was |  |

| TRANSITION | SCRIPT | |
|---|---|---|
| **CLICK TRANSITION (lithium forms)** | Lithium, which has 3 protons, and is created by colliding a helium nucleus with tritium. |  |
| **NEXT SLIDE (look at H, He, Li)** | So, at this point, our universe is essentially composed of gas clouds of hydrogen, helium, & lithium nuclei. |  |
| **CLICK TRANSITION (hydrogen highlight)** | Hydrogen is by far the most abundant of these elements, making up about 75% of the total nuclei in the universe at this time. |  |
| **CLICK TRANSITION (helium highlight)** | Helium is the second most abundant at 25%, |  |
| **CLICK TRANSITION (lithium highlight)** | and lithium only makes up about a billionth of a percent! |  |
| **CLICK TRANSITION (darken, time change)** | At this age of just 15 minutes, the universe has expanded so much that it is now too cool for any heavier elements to form through Big Bang fusion. |  |
| **CLICK TRANSITION (highlight other elements)** | But as you can see in our periodic table, there are still over 100 elements left to form! So what now? |  |
| **CLICK TRANSITION (unhighlight)** | Now we must wait for a new way to make elements. And this wait won't just be a few more minutes, or even a few more months. |  |
| **CLICK TRANSITION (fade to black)** | For the next 300 million years, the universe must undergo drastic changes in order for the rest of the elements to finally form.^ |  |
| **NEXT SLIDE (nuclei)** | The nuclei of these first three elements binds with the electrons, |  |
| **CLICK TRANSITION (atom/electron fade in)** | finally creating clouds of fully formed atoms. |  |
| **NEXT SLIDE (CMB)** | And as a result, radiation is emitted, and the universe is bathed in a cosmic microwave background. |  |

STAR FORMATION & MASSIVE STARS

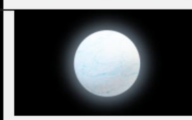
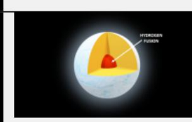
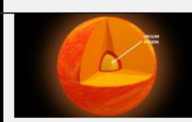
| TRANSITION | SCRIPT | |
|---|---|---|
| **NEXT SLIDE (plays video)** | Next, the force of gravity slowly pulls these cool clouds of hydrogen & helium gas together, accumulating mass and generating heat. |  |

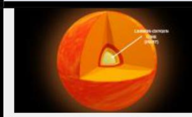
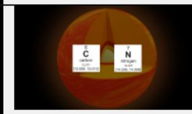
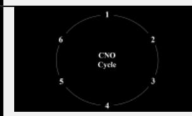
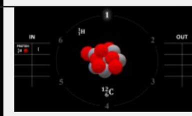
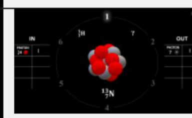
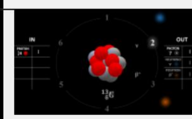
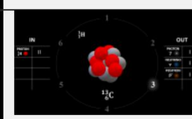
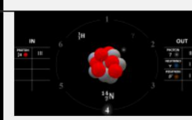
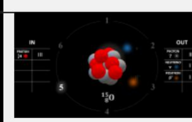
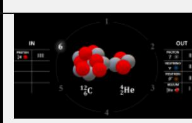
| TRANSITION | SCRIPT | |
|---|---|---|
| **(Continues playing)** | These massive, contracting gas clouds are called protostars. Self-gravitation causes these protostars to continue contracting and heating up, until their cores reach over 10 million degrees. |  |
| **(Zooms in)** | At this point, hundreds of millions of years later, it is once again hot enough for hydrogen fusion to occur… |  |
| **NEXT SLIDE (fades to first star)** | And thus, stars are born! |  |
| **(Continues fading)** | This hydrogen-fusing stage is actually the longest stage in a star's lifetime - Any given star will spend about 90% of its total lifetime burning hydrogen. |  |
| **CLICK TRANSITION (zoom out to stars)** | Though all stars begin in this way, the details of the rest of a star's life cycle and the specific elements it creates can differ significantly depending on its mass. |  |
| **CLICK TRANSITION (zoom into star)** | Let's start by looking at the stars with the shortest lifetimes, as they were the first in our universe to create the heavier elements. |  |
| **NEXT SLIDE (white screen fade)** | These shortest-lived stars are called the massive stars, |  |
| **CLICK TRANSITION (zoom in to massive star)** | and they are 8 or more times the mass of our Sun. Just like all stars, a massive star begins its lifetime fusing |  |
| **CLICK TRANSITION (cut-away )** | hydrogen to helium in its core through a process called stellar fusion. A star of this size will spend about 3 million years in this hydrogen fusion stage! |  |
| **NEXT SLIDE (fade to red supergiant, He core)** | Over this time, the helium slowly accumulates at the core, and a shell of hydrogen fusion is pushed out around it. |  |
| **CLICK TRANSITION (He fusion label)** | Once this helium core becomes hot enough, helium fusion is ignited, and carbon & oxygen begin to form. |  |
| **CLICK TRANSITION (C-O core)** | Over the course of the next 300,000 years, the carbon & oxygen will accumulate in the core of the massive star. |  |
| **CLICK TRANSITION (C-O fusion label)** | Once this carbon & oxygen core is hot enough, carbon fusion is ignited, |  |
| **CLICK TRANSITION (O-Ne-Mg core)** | and oxygen, neon, and magnesium will form in the core for the next 1,000 years. |  |

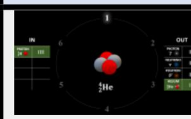
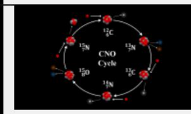
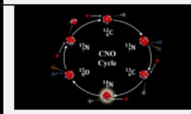
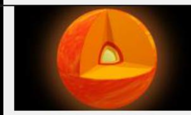
| TRANSITION | SCRIPT | |
|---|---|---|
| **CONTINUE CLICKING** **(progress up to Si core)** | This cycle of fusing progressively heavier elements at the core continues all the way up to silicon fusion, which only lasts for about 1 day!<br>The fusion of these elements is what gives a star its energy, its fuel to burn, and its starlight. But as it begins forming the next elements, iron & nickel, the massive star starts running out of fuel. |  |
| **CLICK TRANSITION (Fe-Ni core)** | An iron & nickel core will form, but these elements are so heavy that the process of fusing them would actually consume more energy than it produces. Thus, iron fusion will never occur, and iron & nickel are the last elements that this massive star will create. |  |
| **CLICK TRANSITION (shell/core labels)** | So now we have all these new, heavy elements produced within the massive star, but how do they get out of the star and into the rest of the universe? |  |
| **NEXT SLIDE (solid red supergiant)** | Well, because fusion is no longer occurring in the core of the star, |  |
| **CLICK TRANSITION (zoom out of star)** | it soon becomes unstable and collapses under its own gravity. |  |
| **(supernova video plays)** | The core falls inward at super high speeds, causing a shock wave to propagate back outwards through the star. This blows off the entire outer part of the star in an unbelievably bright, hot |  |
| **(to end of video, white screen)** | explosion. This is what we call a core-collapse supernova. |  |
| **(white fades to crab nebula, zooms in slowly)** | The gas that was ejected outward by the supernova continues to slowly expand, mixing with the interstellar gas around it. |  |
| **(crab nebula zooms, Vela nebula remnant fades in)** | This cloud of ejected gas becomes much like the one we saw earlier – |  |
| **(Vela fades out & zooms, W3 star forming regions fades in)** | Over time, regions of gas will contract and heat up, create protostars, and eventually go on to form the next generation of stars. |  |
| **(W3 continues to zoom in)** | This time, however, the stars will not be formed from hydrogen and helium gas alone – The gas will be rich with the heavy metals that were created and ejected by the supernova. |  |

| TRANSITION | SCRIPT | |
|---|---|---|
| **NEXT SLIDE (periodic table, fades in new elements except Fe & Ni)** | This includes elements like oxygen, magnesium, neon, silicon, calcium, and titanium, just to name a few. |  |
| **CLICK TRANSITION (adds up to Ni)** | This nebula will also contain a little bit of iron & nickel. So now we've filled out our periodic table quite a bit, and we can see here which elements originate from exploding massive stars. But clearly, we still have many elements unaccounted for. |  |
| **CLICK TRANSITION (highlight heavier elements)** | Where did the elements heavier than iron & nickel come from? |  |
| **CLICK TRANSITION (highlight C & N)** | What about the remaining carbon and nitrogen that we find in our universe? |  |

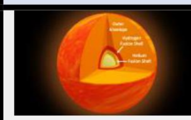
INTERMEDIATE MASS STARS

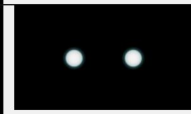
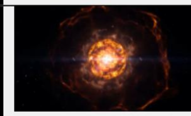
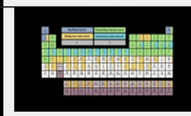
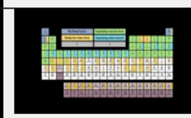
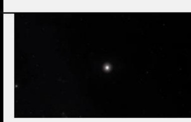
| TRANSITION | SCRIPT | |
|---|---|---|
| **NEXT SLIDE (periodic table fades)** | To find the origins of these elements, we must look to the stars once again, and shift our focus to the smaller, intermediate mass stars. |  |
| **NEXT SLIDE (zoom to int. mass star)** | Let's take a look at this star here, which is about 2-4 times the mass of our Sun. Just like a massive star, this intermediate mass star begins its life when the core is hot and dense enough for |  |
| **CLICK TRANSITION (cut-away of H fusion core)** | hydrogen fusion to occur. Helium is produced and accumulates in the core. |  |
| **NEXT SLIDE (star swells, helium fusion label)** | Eventually, the helium core becomes large enough & hot enough for helium fusion to ignite. |  |
| **CLICK TRANSITION (C&O core, with label)** | Now, carbon and oxygen are produced and begin to accumulate in the core. So far, this process seems identical to what occurred inside the massive star, but our intermediate mass star won't go any further than this. A star of this size will never reach the point of forming heavier elements like silicon, iron, or nickel. |  |

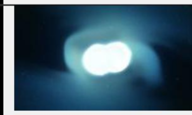
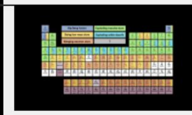
| TRANSITION | SCRIPT | |
|---|---|---|
| **CLICK TRANSITION**<br>**(inert core label)** | The carbon-oxygen core in this star is simply not massive enough, so carbon fusion cannot ignite, and we're left with an inert core. Although this star can't fuse as many heavy elements in its core, it does something else that massive stars cannot. |  |
| **CLICK TRANSITION**<br>**(fade, C&N appear)** | Intermediate mass stars produce the vast majority of the carbon and nitrogen in our universe. These are some of the most important elements for life; We wouldn't be here without them. |  |
| **CLICK TRANSITION**<br>**(C&N fade away, H shell label appears)** | These elements are created right here in the hydrogen fusion shell through a process called the Carbon-Nitrogen-Oxygen (or CNO) cycle. |  |
| **NEXT SLIDE**<br>**(Go to CNO Cycle)** | This cycle is responsible for the production of helium in the star, and it's composed of 6 main steps. |  |
| **CLICK TRANSITION**<br>**(Go to and play step 1)** | It begins when a nucleus of carbon-12 is fused with a proton, creating a nucleus of nitrogen-13 and emitting a photon. |  |
| **CLICK TRANSITION**<br>**(Go to step 2)** | Because nitrogen-13 is unstable, it will quickly undergo a process called positron decay. |  |
| **CLICK TRANSITION**<br>**(Play step 2)** | One proton is converted into a neutron, and two particles called a neutrino and a positron are emitted. Now we have a nucleus of carbon-13. |  |
| **CLICK TRANSITION**<br>**(Go to and play step 3)** | When a second proton fuses with carbon-13, another photon is emitted and nitrogen-14 is created. This is the most common type of nitrogen in our universe. |  |
| **CLICK TRANSITION**<br>**(Go to and play step 4)** | A third proton then fuses with the nucleus, emitting a photon and creating oxygen-15. |  |
| **CLICK TRANSITION**<br>**(Go to and play step 5)** | This is another unstable nucleus, so positron decay occurs once again. A proton is converted into a neutron, and a neutrino and a positron are emitted. Now we have a nucleus of nitrogen-15. |  |
| **CLICK TRANSITION**<br>**(Go to and play step 6)** | A fourth and final proton fuses with the nitrogen-15 nucleus, but this time, the nucleus is split into two smaller nuclei: Helium, and carbon-12, which is where the cycle began. |  |

| TRANSITION | SCRIPT | |
|---|---|---|
| **CLICK TRANSITION** **(Highlight products and reactants)** | As you can see from the inventory tables on the side, the CNO cycle involves 4 hydrogen nuclei fusing one helium nucleus - In this reaction, the carbon, nitrogen, and oxygen are acting only as catalysts, not products. |  |
| **NEXT SLIDE** **(Full CNO cycle)** | How then is this cycle so crucial for production of nitrogen? |  |
| **CLICK TRANSITION** **(Highlight 4th step)** | While nitrogen-14 is only one step in the CNO cycle, it is the longest stage in the cycle by far. If we were to somehow freeze the CNO cycle at some random time, we would find the majority of the nuclei in this nitrogen forming stage. |  |
| **NEXT SLIDE** **(Go back to red giant)** | Luckily, this “freezing” of the CNO cycle actually occurs at the end of this star’s life cycle. |  |

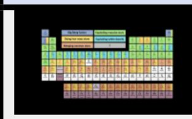
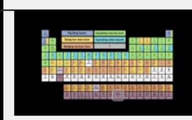
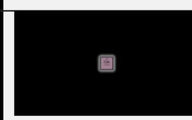
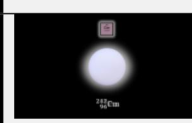
DYING STARS

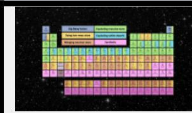
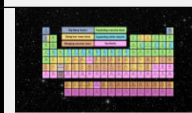
| TRANSITION | SCRIPT | |
|---|---|---|
| **CLICK TRANSITION** **(Turn on labels)** | Once the star runs out of fuel in its core, it becomes unstable and ejects its outer envelope. The hydrogen fusion shell and the helium fusion shell are lifted off with it. |  |
| **NEXT SLIDE** **(Play helix nebula formation video)** | This ejection creates a planetary nebula like the one you see here. When the hydrogen fusion shell was lifted off, the CNO cycle was suddenly stopped, and most of the nuclei were in the form of nitrogen-14. |  |
| **(Continues playing)** | When the helium fusion shell was lifted off, its production of carbon and oxygen was also halted, and most of those nuclei were in the form of carbon at the time. |  |
| **(Transitions to helix nebula fulldome video)** | This nitrogen- and carbon- rich gas of the nebula will continue expanding and mixing with the interstellar gas around it. This is where most of the carbon and nitrogen we see today came from. |  |
| **CLICK TRANSITION** **(Zoom through nebula)** | But what else is left behind? What was once the core of an intermediate mass star has now become a dim, dense, white dwarf star. |  |

| TRANSITION | SCRIPT | |
|---|---|---|
| **(Transitions to white dwarf)** | No fusion can occur inside a white dwarf, so it slowly cools down over billions and billions of years until it no longer emits any significant amount of energy. |  |
| **CLICK TRANSITION** **(Pull up second white dwarf)** | It seems that the story of the intermediate mass star has come to end, and it has, unless it happens to find itself in orbit with a second white dwarf. |  |
| **NEXT SLIDE** **(Play WD merger video)** | Over time, the two white dwarfs can spiral inward toward each other, and eventually become a singular mass. |  |
| **(Continues playing)** | If this combined mass exceeds a certain limit, it is unable to hold itself up against its own gravity, and a huge explosion called a thermonuclear supernova occurs. |  |
| **(Continues playing)** | This explosion causes rapid fusion reactions to occur, creating some silicon, calcium, sulfur, and nickel, but mainly creating lots of iron. |  |
| **NEXT SLIDE** **(Periodic table)** | As you can see on our periodic table, we've now learned where nearly half of the elements in our universe come from! But we still haven't accounted for the very heavy elements, like platinum, gold, and uranium. |  |
| | To create these very heavy elements, we'll need lots of energy, lots of heavy elements like iron and nickel, and lots of neutrons. These conditions can be found in the remnants of massive stars. |  |
| **NEXT SLIDE** **(Play supernova video)** | So let's go back and take a closer look at the end of the massive star's lifetime. Recall that when the core runs out of fuel from fusion, it collapses in on itself. |  |
| **(Continues playing)** | At these extremely high temperatures and pressures, the electrons and protons in the core can combine to form lots and lots of neutrons through a process called electron capture. |  |
| **(Continues playing)** | This process releases tons of neutrinos, which push the outer envelope and fusion shells off of the core in a supernova. |  |
| **NEXT SLIDE** **(Fade to neutron star)** | What's left behind is called a neutron star. In this dense, neutron-rich environment, some heavy elements could be formed as the huge winds of neutrinos push out from the core. |  |
| **CLICK TRANSITION** **(Bring in second neutron star)** | Another likely source of heavy elements occurs when a second neutron star comes into the picture. |  |

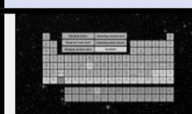
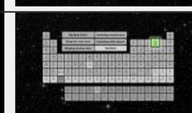
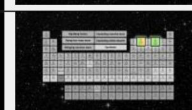
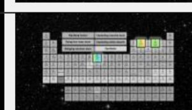
| TRANSITION | SCRIPT | |
|---|---|---|
| **CLICK TRANSITION** **(Play NS merger video)** | Much like we saw with the white dwarf stars, two neutron stars can be in orbit with one another. This is a very rare occurrence in our universe, and it produces the rarest of the elements. |  |
| **(Continues playing)** | When these neutron stars spiral inward, they merge and result in a massive explosion called a kilonova. |  |
| **(Continues playing)** | This expels lots of neutron-rich material at super-high temperatures, and we believe heavy elements could be rapidly synthesized here. |  |
| **NEXT SLIDE** **(Periodic table)** | As you can see here, there's still a handful of elements left. What kind of event could create elements this large? |  |

SYNTHETIC ELEMENTS

| TRANSITION | SCRIPT | |
|---|---|---|
| **(Stay on periodic table)** | As we'll see, these last nine elements are quite unique, and are created in a very different environment than all the others we've seen before - These are created right here on Earth. |  |
| **CLICK TRANSITION** **(Highlight curium)** | These elements are so heavy that we actually don't find them in nature at all, and they have to be created in a lab. We call these the synthetic elements. Let's take a look at the first synthetic element ever created, curium. |  |
| **CLICK TRANSITION** **(Fade to curium square)** | To create an element this large, it was necessary to use a type of particle accelerator called a cyclotron in order to overcome the repulsive forces that typically keep this element from forming. |  |
| **NEXT SLIDE** **(Play curium animation)** | In this case, a sample of plutonium-239 was bombarded with helium nuclei, creating curium and releasing a neutron. |  |
| **CLICK TRANSITION** **(Show decay)** | However, this curium would quickly decay back into a helium nucleus and a form of plutonium. The other synthetic elements are similarly unstable, and this is one major reason why we don't see them in nature. |  |

| TRANSITION | SCRIPT | |
|---|---|---|
| **NEXT SLIDE**<br>**(Completed periodic table)** | They may even be created naturally somewhere, but they're so rare and so short lived that we don't see them in our universe. But if they're so rare and short lived, why would we want to create them in the first place? |  |
| **(Stay on periodic table)** | Although their origin story isn't quite as flashy, the synthetic elements are a very interesting group. There's something truly incredible about humans creating new elements, especially when you consider that we ourselves are made of elements. |  |

CONCLUSION

| TRANSITION | SCRIPT | |
|---|---|---|
| **NEXT SLIDE**<br>**(B&W periodic table)** | Now that we understand the origins of the elements in our universe, we can also understand the origins of us. |  |
| **CLICK TRANSITION**<br>**(Highlight oxygen)** | The oxygen we breathe, |  |
| **CLICK TRANSITION**<br>**(Highlight carbon)** | the carbon we exhale, |  |
| **CLICK TRANSITION**<br>**(Highlight iron)** | the iron in our blood, |  |
| **CLICK TRANSITION**<br>**(Highlight helium)** | and even the helium in our balloons is created in the stars. |  |
| **NEXT SLIDE**<br>**(Carl Sagan quote)** | "The cosmos is within us. We are a way for the cosmos to know itself." And there is still much left for us to discover. |  |